NASA-CR-195229

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FINAL REPORT

NAGW-1840

Differentiating the Role of Land Surface Variability and Cloudiness Variability on Global Energy Transport within the Atmosphere and Oceans

March 1993

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(NASA-CR-195229) DIFFERENTIATING THE ROLE OF LAND SURFACE VARIABILITY AND CLOUDINESS VARIABILITY ON GLOBAL ENERGY TRANSPORT WITHIN THE ATMOSPHERE AND OCEANS Final Report (Florida State Univ.) 8 p

N94-26222

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1.0 Introduction

The following provides the final report on NASA IDP Project NAGW-1840 "Differentiating the Role of Land Surface Variability on Global Energy Transport within the Atmosphere and Oceans". The project was designed to investigate the role of regional perturbations in the earth radiation budget on atmospheric and oceanic energy transports on an interannual basis. We proposed a modeling strategy based on an entropy extremum principle that could be used to separate the transports into oceanic and atmospheric components so as to better understand the effects of regional perturbations at the distinct atmospheric and oceanic time scales. The original focus was to consider the maintenance and year-to-year modulation of a large-scale, low-latitude North African-West Pacific Ocean net radiation dipole, which we had detected in the Nimbus 6 and 7 record of earth radiation budget measurements, and which necessitated significant cross-meridional energy transports to maintain global equilibrium. In addition, perturbations in the radiation balance term were to be partitioned into cloud-induced and surface-induced components to better understand the feedbacks between clouds and surface boundary conditions on interannual variability of the radiation balance.

The research was conducted over the period from 7-1-89 to 12-31-92. After the project commenced, we expanded the focus to include global scale processes as well as regional scale processes. The main data sets for the project were derived from the Nimbus 7 measurements and included ERB, THIR cloudiness, and SMMR MPD data sets. The research was ultimately divided into three basic topic areas:

1. Coupling Between Surface and Top-of-Atmosphere Radiation Budgets in the African Sahel

2. Cloud-Surface-Radiation Interactions and Their Impact on Required Energy Transports

3. Two Dimensional Decomposition of Atmospheric and Oceanic Energy Transports

Results from the project led to 10 publications, 7 of which were published in refereed journals. The references for these publications are given in Section 3. Section 2 provides a summary of the findings, along with the associated citations.

2.0 Summary of Research Findings

Coupling Between Surface and Top-of-Atmosphere Radiation Budgets in Sahel

Smith and Choudhury (1993) conducted a study that showed interannual variations in the net radiation balance at the top-of-atmosphere over North Africa are linked to variations at the land surface within the Sahelian zone. The spatial distribution of the amplitude of interannual variability of net radiation at the top of the atmosphere was examined using coincident monthly time series of earth radiation budget and passive microwave measurements obtained from the Nimbus 7 satellite over a five year period from 1979 to 1983. A strong association was found between the radiation budget anomalies derived from ERB-WFOV measurements and the anomalies of 37 GHz polarized brightness temperature difference derived from the SMMR measurements. Another study of Choudhury et al. (1993) was conducted to demonstrate the reliability of the 37 GHz MPD data set by considering the potential attenuation by the atmosphere on the estimates. Previous research by Smith and Sohn (1989)[1] had shown that the interannual anomalies in the top-of-atmosphere net radiation balance in the Sahelian zone mostly arise from changes taking place at the surface, not from variations in cloudiness. Since microwave polarization difference is related to vegetation cover, the new results indicated that the main control of the interannual modulation of North Africa's radiation balance is year to year fluctuations of vegetation cover within the Sahelian zone stemming from fluctuations in rainfall, which is intrinsically associated with cloud variability. However TOA interannual net radiation variability is more influenced on how cloud variability impacts the surface through rainfall, than it is through direct cloud-radiation feedback on TOA fluxes. This finding is considered to be relevant to an understanding of how cloud-radiation processes control and feedback on global climate through processes taking place at the surface of a semi-arid zone.

Cloud-Surface-Radiation Interactions and Their Impact on Required Energy Transports

Based on the preliminary findings of Smith and Sohn (1990) and Sohn and Smith (1991), a series of studies were conducted by Sohn and Smith (1992a-c) to show

[1] Smith, E.A., and B.J. Sohn, 1990: Surface forcing of interannual variations in the radiation balance over North Africa. Part I: Partitioning the surface and cloud forcing. *Climatic Change.*, **12**, 5-51.

how cloud-radiation and surface-radiation interactions influence the earth radiation balance and the requirements for energy transport on a global scale. Cloud-radiative forcing calculations based on the Nimbus 7 radiation budget and cloudiness measurements revealed that cloud induced longwave warming (cloud greenhouse influence) is dominant over the tropics whereas cloud induced shortwave cooling (cloud albedo influence) is dominant over the mid and high latitudes. The average SW cloud cooling taken over the area of the globe from 65°N to 65°S was found to be -27.8 $W{\bullet}m^{-2}$. This magnitude slightly overcomes LW cloud warming (-25.7 $W{\bullet}m^{-2}$), resulting in a small net cooling effect of -2.1 $W{\bullet}m^{-2}$ over 93% of the earth.

A six year zonally averaged mean cloudy and clear sky net radiation flux analysis showed that there are three distinct regimes in terms of net cloud warming or cooling, i.e., warming in the tropics (between 20°N and 20°S) and in the high latitudes (poleward of 55°), and cooling in the extratropical latitudes between 20° and 55° in both hemispheres. These distributions reinforce the intensities of the Hadley and Ferrel meridional circulation cells. This stems from strong warming due to high-level clouds in the tropics and strong cooling due to middle and low level clouds at extratropical latitudes. The magnitude of the contribution by cloud forcing was found to be of the same order as eddy heat and momentum flux forcing to the maintenance of the mean meridional circulation.

Surface-atmosphere forcing obtained by differentiating the cloud induced effects from the measured radiative fluxes indicated that an east-west coupled North Africa - Western Pacific energy transport dipole is maintained mainly by low latitude land-ocean contrasts associated with shortwave radiation but supported by cloud controls on tropical longwave radiation. This implied that interannual variations in the net radiation balance associated with these two regions can give rise to fluctuations of the basic dipole structure and thus fundamental changes in low-latitude climate.

The source and forcing mechanisms of radiation budget variability over tropical latitudes were examined by separating the variations into cloud and surface-forced components. A zonal harmonic analysis of emitted longwave radiation showed that these variations are largely controlled at the planetary wave scale. Positive total and cloud-forced longwave (LW) anomalies embedded within this planetary scale structure showed eastward movement from the Indian Ocean toward the Eastern Pacific together with the easterly displacement of negative anomalies from the Western Pacific toward Africa during the period prior to and after the active phase of the 1982-83 ENSO. The overall effect leads to an approximately 50° per year propagation phase speed which is considerably slower than the oceanic Kelvin wave capable of driving east-west LW anomalies through SST feedback. The oceanic Kelvin wave speed is about 60° per month over the Pacific basin in the course of an ENSO cycle. This pointed out that there are longer time scales of climatic signals in the tropical radiation budget.

An examination of time dependent radiative energetics over the tropics revealed that the anomaly LW propagation is mainly due to cloud forcing associated with east-west circulation changes, although surface forcing was found to contribute within the Pacific basin. Since cloud amount changes are directly linked to variations in latent heat release, diabatic heating associated with coupled ocean-atmosphere feedback appeared to be the mechanism responsible for the LW anomaly propagation. An examination of the complete radiation budget over the Maritime Continent and Equatorial Central Pacific during the 1982-83 ENSO event demonstrated that radiative forcing produces positive feedbacks in conjunction with the sea surface temperature anomalies that develop in both regions. Furthermore, surface forcing was found to be an important control on net radiation variability within this teleconnection. An examination of two additional tropical east-west teleconnections showed that surface forcing is even more important than cloud forcing in controlling variations in the east-west net radiation gradients.

The impact of differential net radiative heating on two-dimensional energy transports within the atmosphere-ocean system and the role of clouds on this process were then examined. The radiation budget data showed basic energy surpluses over the tropical oceans and relative or absolute energy deficits over low latitude continental regions. The two-dimensional mean energy transports, in response to zonal and meridional gradients in the net radiation field, exhibited an east-west coupled dipole structure in which the West Pacific acts as the major energy source and North Africa as the major energy sink. It was shown that the dipole is embedded in the secondary energy transports arising mainly from the differential heating between land and oceans in the tropics in which the tropical east-west (zonal) transports are up to 30% of the tropical north-south (meridional) transports. Thus, any perturbations to this dipole on an interannual basis due to regionally induced fluctuations of the net radiation balance, give rise to low latitude energy transport variations. In turn, the tropical variations lead to extratropical responses through alterations of requirements on both zonal and meridional transports at all positions on the globe. Cloud-induced transports, obtained by differentiating the cloud-free portion from the total transport field, indicated that year-to-year cloud amount changes are contributing to fluctuations of the global climate system through these mechanisms.

Increased cloudiness increases zonal available potential energy thus increasing the intensity of the north-south transports while slightly weakening the dipole intensity. It thus appeared that the basic role of cloudiness is to diminish the role of differential heating between continents and oceans and force the globe toward a more meridionally distributed energy imbalance. This implied that the radiative feedback effects of clouds, regardless of factors determining cloud amount variability, reduce the radiative decoupling of land and ocean. This conclusion cannot be arrived at heuristically because it pertains to the specific optical properties of continental and oceanic cloud systems and additional factors governing cloud amount variability over the land masses and oceans themselves.

Two Dimensional Decomposition of Atmospheric and Oceanic Energy Transports

Our final application of the Nimbus 7 cloud and radiation budget measurements concerned a new method to decompose the required oceanic and atmospheric energy transports in two dimensions. The studies of Sohn and Smith (1992d, 1993) showed how the total required transport field, as determined from net radiation measurements, could be separated into the separate components by applying a maximum entropy production principle to the atmospheric system. The results showed strong poleward fluxes by the oceans in the northern hemisphere exhibiting a maximum of $2.4\,10^{15}$ W at 18°N, with maximum atmospheric transports found at 37°N with a magnitude of $4.5\,10^{15}$ W. These results were found to be in good agreement with other published results.

In the southern hemisphere, atmospheric transports were found to be considerably stronger than oceanic transports, corroborating findings based on other published direct estimates. Maximum atmospheric energy transports were found at 37°S with a magnitude of $4.7\,10^{15}$ W; two local oceanic transport maxima were shown at 18°S and 45°S with magnitudes of $1.3\,10^{15}$ W and $1.1\,10^{15}$ W, respectively. Results showed evidence of net cross-equatorial transport in which the southern hemisphere oceans give rise to a net transfer of heat northward across the equator, exceeding a net transfer from northern to southern hemisphere by the atmosphere. Since the southern hemisphere results should have the same degree of accuracy as the northern hemisphere results, our findings suggested that southern ocean transports are weaker than previously reported. A main finding of the study was that a maximum entropy production principle can serve as a governing rule on macroscale global climate, and in conjunction with conventional satellite measurements of the net radiation balance, provides a means to decompose atmosphere and ocean transports from the total transport field.

Furthermore, the modeling methodology provided a means to partition the transports in a two-dimensional framework. Sohn and Smith (1994) tested the approach on the separate ocean basins using the maximum entropy production (MEP) principle extended to two-dimensions. In terms of the meridional component of the ocean transport vectors, the results showed northward ocean transports throughout the entire Atlantic ocean from southern hemisphere high latitudes to northern hemisphere polar regions, southward transports throughout the entire Indian Ocean, and poleward transports separated at approximately 10°S in the Pacific Ocean.

The ocean transport patterns were found to be consistent with well-known features concerning heat transport within the three ocean basins. However, uncertainty remained in the magnitudes of the transports. Because of the large remaining discrepancies between published estimates based on direct measurements and indirect estimates derived from energy budget methods, assessing the accuracy of the satellite-based magnitudes was difficult, although there was evidence that limitations in the spatial resolution of the model led to synergistic biases in the North Atlantic and North Pacific.

In terms of the cross-meridional energy transport component, the results suggested that most of the net energy transfer in the tropics takes place within the oceans. In the southern hemisphere high latitudes, the Pacific and Indian Oceans were found to export heat cross-meridionally to the Atlantic Ocean through the passages below Cape Horn and the Cape of Good Hope, although the magnitudes of these inter-ocean heat exchanges were small. Another important aspect of the southern hemisphere results was that poleward transports were dominated by the atmospheric component with strong zonal asymmetry. By contrast, in the northern hemisphere, atmospheric transports over the ocean were generally weaker than the corresponding southern hemisphere terms, indicating that the northern hemisphere oceans are relatively more effective in transferring heat poleward. Finally, poleward atmospheric transports over the continental areas exceeded those over the ocean at equivalent latitudes as a result of the generally greater energy deficits over the land areas.

3.0 Publications Produced Under Grant

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Sohn, B.J., and E.A. Smith, 1994: Energy transports by ocean and atmosphere based on an entropy extremum principle. Part II: Two dimensional transports. *Meteor. Atmos. Phys.*, **51**, in press.

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